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Life Cycle Assessment of Bitcoin Mining

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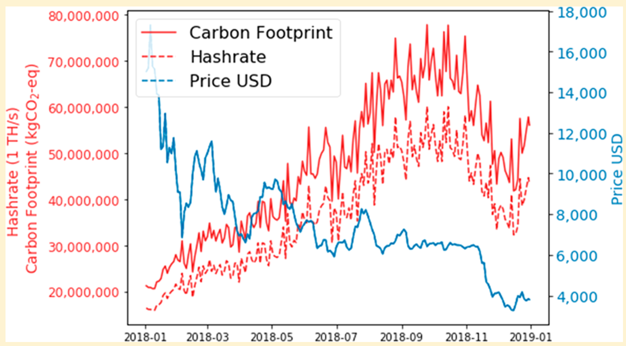
Supporting Information

ABSTRACT: This study estimates the environmental impact of mining Bitcoin, the most well-known blockchain-based cryptocurrency, and contributes to the discussion on the technology's supposedly large energy consumption and carbon footprint. The lack of a robust methodological framework and of accurate data on key factors determining Bitcoin's impact have so far been the main obstacles in such an assessment. This study applied the well-established Life Cycle Assessment methodology to an in-depth analysis of drivers of past and future environmental impacts of the Bitcoin mining network. It was found that, in 2018, the Bitcoin network consumed 31.29 TWh with a carbon footprint of 17.29 $MtCO_2$-eq, an estimate that is in the lower end of the range of results from previous studies. The main drivers of such impact were found to be the geographical distribution of miners and the efficiency of the mining equipment. In contrast to previous studies, it was found that the service life, production, and end-of-life of such equipment had only a minor contribution to the total impact, and that while the overall hashrate is expected to increase, the energy consumption and environmental footprint per TH mined is expected to decrease.



INTRODUCTION

Today, there are many expectations that blockchain technology will change the world for the better.[1−6] The technology is, in extreme synthesis, a distributed ledger that removes the middlemen and establishes trust between unknown parties.[2] Currently, the most mature implementations of blockchain are in the financial sector[7] with the cryptocurrency Bitcoin being a prominent example.[8,9]

While in traditional finance, banks act as a trusted authority and keep track of transactions and balances, in the Bitcoin network, the entire memory of transactions is stored digitally in "blocks" that are linked as a chain—hence blockchain—and kept by a network of peers. A consensus mechanism is how the peers in the Bitcoin network continuously agree on the order of newly added blocks and thus secure the data in a decentralized fashion. Bitcoin's consensus mechanism is based on a proof-of-work (PoW) approach where peers in a network compete in winning the right to add the next block to the chain, a process called "Bitcoin mining" that is performed by "miners". The miners compete in solving a puzzle, which requires substantial computational power. To do so the miners try to find a "nonce value", which is a random value. Every time the miners guess the nonce value an algorithm is applied that maps the data of their suggested block—including the guessed nonce value—–to a value of a fixed length. This output value is called a hash. A miner wins the right to add a new block when this hash is lower than a target value.[10] The target value of the puzzle is adjusted automatically so that, on average, only one block is mined every 10 min.[11] Thus, the more miners join the network or the more efficient miners become, the more difficult it becomes to mine a block, while the block generation time remains approximately constant. The hashrate corresponds to the number of hashes guessed per second. In 2018, the hashrate of the entire Bitcoin network ranged from around 15 to 60 million Tera hashes (TH) per second.[12]

With the increasing popularity of cryptocurrencies concerns were raised regarding the sustainability of Bitcoin, under the rationale that since the Bitcoin network uses a high amount of electricity for mining, its environmental impact might be substantial. A wide range of estimates of Bitcoin's energy consumption have been published in the media, reflecting the uncertainty of such assessments. For example, claiming that Bitcoin mining uses more energy than mining gold,[13] is equal to Switzerland's energy consumption,[14] was to use all the world's energy by 2020,[15] and be alone responsible for not reaching the Paris Agreement.[16] Recent studies—both in gray and academic literature—estimate the energy consumption of Bitcoin to be 22−67 TWh/yr (mid-March 2018),[17] 43 TWh/yr (October 2018),[18] 45 TWh/yr (November 2018),[19] 62 TWh/yr (average of 2018),[20] 39−83 TWh/yr (mid-November 2018),[21] and 105.82 TWh/yr (29 July 2018).[22]

Stoll et al. estimate the annual carbon emissions of Bitcoin between 22.0 and 22.9 $MtCO_2$ (November 2018).[19] Digiconomist proposes the estimate of 30.35 $MtCO_2$/yr[20] (average 2018). McCook[22] estimated the carbon footprint to

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be 63 $MtCO_2$/yr (July 2018). These numbers are contested by Bendiksen et al.[23] who estimate that 77.6% of Bitcoin mining is powered by renewables, while Rauchs et al.[21] report the share of renewables to be around 28%.

A common feature of the previously mentioned studies is that the assessment of environmental impacts is built on ad-hoc methods. For example, McCook[22] uses global emission factors only and Digiconomist[20] assumes 70% of miners to be located in China and the rest impact free. Despite the substantial uncertainties in the data and choices used in previous models, an explicit uncertainty assessment is lacking in previous studies. There is thus the need to use a solid methodological basis to increase the transparency, validity, and replicability of the environmental assessment of Bitcoin.

A well-established approach to assess environmental impact is Life Cycle Assessment (LCA).[24] LCA allows for a detailed analysis of a system including all stages from raw material extraction through production processes, use phase, and disposal or recycling.[25] Previous studies have used LCA to study different emerging technologies[26] from power generation,[27,28] electric vehicles,[29] resource recovery from e-waste,[30] to food processing.[31] The challenge of prospective analysis is that data gaps are substantial and need to be dealt with accordingly,[32] for example, by means of scenario development, or by applying techniques for sensitivity and uncertainty analysis.[32]

Summing up, previous studies assessing the impact of the Bitcoin mining network show contrasting and arguably overestimated results, and a key challenge in this assessment is the scarcity of accurate data on key factors determining the impact of the mining network. This study wants to bring new insights in this area by providing a more detailed analysis of the hotspots of environmental impact in the Bitcoin mining network and by increasing the accuracy in the modeling of regional electricity mixes. Furthermore, this study wants to add a prospective approach by considering how electricity generation or the geography of the mining network might change in the future. The added value of this analysis is adopting LCA as robust scientific methodology, the use of established databases for assessing environmental impact, including the impact of mining equipment in the analysis, and providing an outlook of future impacts.

■ METHODS AND MATERIALS

This study takes both a retrospective and a prospective approach, and two different system models were respectively used. The retrospective analysis was conducted via attributional LCA, the prospective one via consequential LCA.[33] The attributional model was used to determine environmental impacts of the Bitcoin network in 2018, whereas the consequential LCA to estimate the environmental consequences of an increase in Bitcoin mining in the future. The retrospective analysis only assesses the impacts for 2018, because the hashrate before 2018 was significantly lower, 17 million TH/s at its top,[12] and a historic analysis would require data on the location of miners and their mining equipment for every distinct period in the system, which is either not available or highly uncertain. Figure 1 shows the structure of the product system that was analyzed in both cases. The ecoinvent v3.5 database was used for background modeling, the allocation at the point of substitution (APOS) database for the retrospective model, and the consequential one for the prospective model.[34] The impact of such a system was

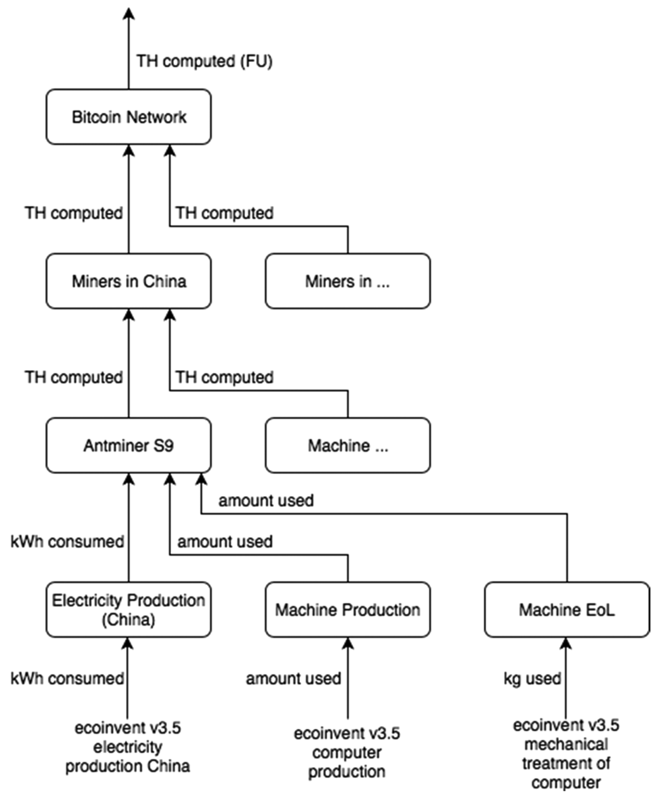

Figure 1. Structure of the product system under analysis. Boxes indicate activities in the foreground system. Arrows indicate exchanges. TH = tera hashes. FU = functional unit.

determined in multiple midpoint impact categories[35] using the IPCC[36] and ReCiPe[37] methods. In the text, the IPCC method is reported for the carbon footprint. To understand the uncertainty associated with the background data, Monte Carlo simulations with 1000 iterations were carried out for the attributional baseline model and each consequential scenario.[38,39] All analyses were performed using the Brightway2 open source LCA software.[40] Results can be reproduced by using code available in a GitHub repository[41] so that the results are transparent and can easily be reproduced.

Functional Unit for the Attributional Model. The functional unit of the attributional model was defined as computing 1 TH. This choice was motivated by the fact that with a constantly changing hashrate, between 15 and 60 million TH/second in 2018 alone,[12] using a specific rate would not allow comparisons between studies that have been carried out at different points in time. Instead, the impact associated with computing 1 TH can then be linearly upscaled to obtain the impact of Bitcoin for a given period according to the actual hashrate, which can be determined using available data on the network's hashrate.[12]

Bitcoin Network in the Attributional Baseline Model. The information currently available on the location of Bitcoin miners is scarce and inaccurate. However, this information is crucial for estimating the environmental impact of the Bitcoin network, which is highly dependent on the electricity mix of the geographical locations where mining is performed. A geographical distribution of the Bitcoin mining network was developed in this study based on information available from two previous studies, Bendiksen et al.[23] and Rauchs et al.,[21] as well as own research on mining pools.[42] Details on the

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methodology used to derive this geographical distribution are provided in Supporting Information (SI) Section 2. Table 1 shows the geographical distribution of the miners used in the attributional baseline model for 2018.

Table 1. Geographic Distribution of Bitcoin Miners Used in the Attributional Baseline Model

location	share
China	53.5%
Inner Mongolia	12.3%
Xinjiang	10.7%
Sichuan	30.5%
Canada	12.8%
Quebec	4.0%
British Columbia	4.1%
Alberta	4.7%
U.S.	13.7%
New York state	7.5%
Washington state	6.2%
Iceland	4%
Georgia	4%
Norway	4%
Sweden	4%
Russia	4%

Mining Activities in the Attributional Baseline Model. Besides the energy mix, the electricity consumption of the Bitcoin network depends also on the equipment used for mining as it determines the efficiency of mining, namely the electricity consumption per TH computed. The types of equipment included in the model are taken from Bendiksen et al.[23] 79.9% of the miners modeled are Antminer S9, 7.6% Avalon 841, 6.7% Ebang E10, and the remaining 5.8% are modeled as other machines. Details on the methodology used to derive these values are provided in SI Section 4.

Mining Equipment in the Attributional Baseline Model. The use of mining equipment involves three main activities: electricity consumption, production, and end-of-life (EoL) of the equipment.

The main contributor to electricity consumption is the use of electricity for mining, determined according to the product specifications of each machine. Large facilities, especially in warmer climates, may require additional energy for cooling and other inefficiency. In the model, an additional electricity use of 5% was assumed based on Stoll et al.[19] The consumption of electricity was modeled using the electricity mix from the ecoinvent v3.5 APOS database of each country where the miners are located.[34]

The amount of equipment that is produced and hence needs to be disposed of is approximated using machine lifetime. According to Digiconomist,[43] Bitcoin mining equipment has an average lifetime of 1.5 years, a figure that was also used in this model. For the production of mining equipment, the ecoinvent v3.5 process for "market for desktop computer without screen" was chosen.[44] Since this data set refers to a computer with a weight of 11.3 kg and the mining equipment is much lighter (e.g., 4.2 kg for an Antminer S9), the amount used as input was corrected taking into account the weight difference (e.g., 4.2/11.3 kg desktop computer for the Antminer S9). Similarly, for the end-of-life of the machines, the ecoinvent v3.5. process "mechanical treatment of used desktop computer" for 1 kg of equipment was selected[45] and scaled to the weight of the mining equipment.

Sensitivity Analysis in the Attributional Baseline Model. A sensitivity analysis was carried out to identify how key modeling parameters and modeling assumptions affect the results.

First, the sensitivity to the electricity mix and geographical distribution of miners was investigated. Three different electricity mixes were modeled: 100% hydropower-based representing a best case; 100% coal-based representing a worse case; and a global average mix. Then, three divergent geographic distributions were modeled. The "Cambridge Centre for Alternative Finance" distribution—in short CCAF distribution—is based on Rauchs et al.[21] It is important to highlight that only 1.7 GW of the mining capacity has been captured in the study by Rauchs et al.,[21] and it is not limited to Bitcoin as mining activities of the four largest cryptocurrencies are included.[21] The "CoinShares" distribution is based on Bendiksen et al.[23] who identify major regions of Bitcoin mining and distribute the mining activities evenly among those areas. The "Mining Pools" distribution is based on information about the mining pools that successfully mined Bitcoin in 2018.[42] Details on the methodology used to derive each geographical distribution are provided in SI Section 2.

Next, the sensitivity of the baseline model with respect to other key parameters was tested. This allowed to understand the effect of improving mining efficiency or increasing electricity consumption. The sensitivity of the model results was tested with respect to (1) a 10% increase in energy consumption; (2) a 10% decrease in energy consumption; (3) a 10% increase in the hashrate of the mining equipment; (4) a 10% decrease in the hashrate of the mining equipment; and a change in the lifetime of the mining equipment to (5) 1 year and (6) 2 years.

Consequential Model. The consequential approach is fundamentally different from the attributional one as it focuses on quantifying the effect of an increase in the demand for mining. In the consequential LCA, three different scenarios were modeled.

The first model describes a business-as-usual (BAU) scenario that differs from the attributional baseline model only in the background system: the consequential version of the ecoinvent v3.5 database instead of the attributional (APOS) version.[34] This model describes a situation where the geographical distribution of miners is irresponsive to changes in demand for mining, but the surrounding energy system and electricity network is responsive to changes in demand for electricity.

The second model describes a technology-sensitive scenario where an increase in demand for mining will be met by installing new mining capacity and investing in the most efficient mining equipment. In other words, in this model only the marginal mining technologies are included.

The third model describes a location-sensitive scenario where an increase in demand for mining is met not only by installing efficient mining capacity, but also by changing the geographical distribution of the miners toward locations that allow for more competitive conditions (e.g., lower energy prices and temperatures).

Functional Unit of the Consequential Model. The functional unit of the consequential model was defined as increase in demand for computing 1 additional TH. The consequential model thus investigates the effect associated

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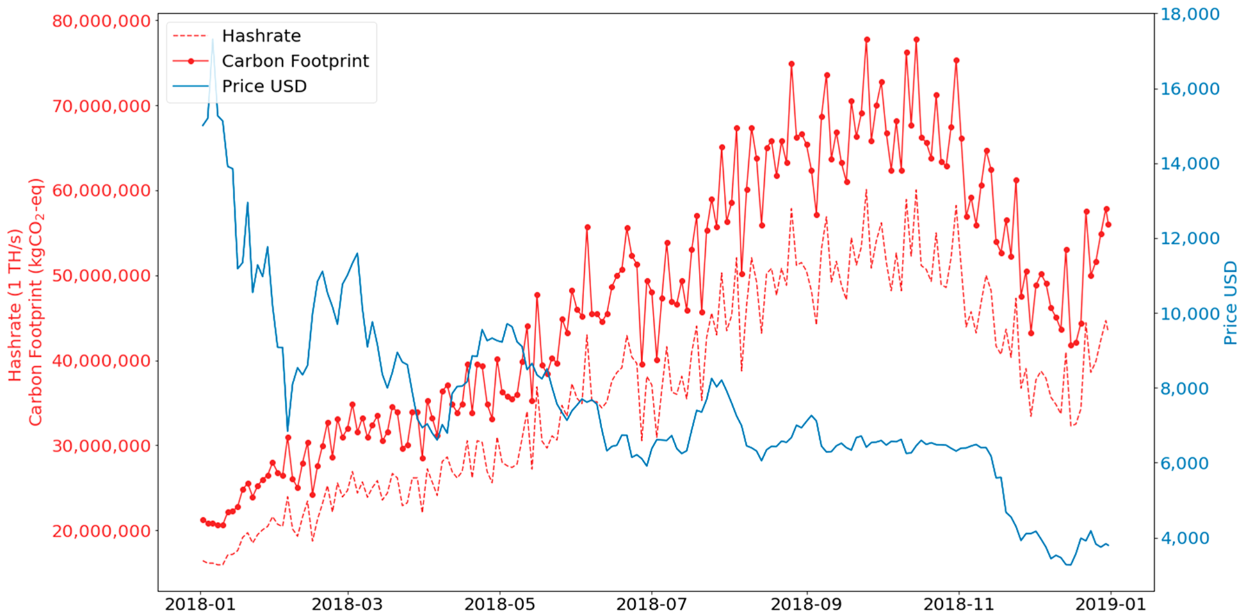

Figure 2. Carbon footprint of Bitcoin in 2018 compared to the market price and the hashrate.

with a marginal increase in mining rather than the total absolute impact of the whole mining.

Bitcoin Network in the Consequential Model. In the BAU and technology scenarios, the same geographical distribution of miners was maintained as in the attributional baseline model (Table 1). In the location scenario, the geographical distribution was adjusted to only include locations where miners are opening new facilities. With a changing political environment in China,[46,47] miners are looking for new locations with cheap electricity, fast Internet, and low temperatures. According to Bendiksen et al.[23] as well as several media articles[48−52] new mining facilities have been opened in parts of Scandinavia, North America, and Russia. Thus, in the location scenario the miners were assumed to be equally distributed among Norway, Sweden, Iceland, Russia, Canada, and the U.S.

Mining Activities in the Consequential Model. In the BAU scenario, the same mining equipment as in the attributional model was used, which has an overall efficiency of 0.095 J/GH. In the technology and location scenarios the model includes only the most efficient mining equipment currently on the market. No data is available on how the share of different types of mining equipment has changed over time so this modeling relies heavily on the Authors' assumptions, and should be therefore taken as an explorative scenario exercise. It was assumed that the marginal mix of mining equipment would be composed of 70% of Antminer S15, 20% of Ebang E11++, and 10% of Avalon 1041. With this distribution of mining equipment an overall efficiency of 0.0545 J/GH is reached, which is 42.6% more efficient then the mining equipment of the BAU scenario.

Mining Equipment in the Consequential Model. Regarding additional electricity for cooling and other inefficiency as well as the lifetime of mining equipment, all three consequential scenarios maintain the same assumptions as in the attributional baseline model. In contrast to the attributional model, all three consequential scenarios are linked to the ecoinvent v3.5 consequential database.[34]

RESULTS AND DISCUSSION

In the attributional baseline model, the energy consumption for every TH mined is 27.14 mWh. That means that the Bitcoin network consumed 31.29 TWh in 2018. As expected this value is consistent with previous studies (22−67 TWh/yr,[17] 45 TWh/yr,[19] 62 TWh/yr,[20] 39−83 TWh/yr,[21] 105.82 TWh/yr[22]) given the similar assumptions. Deviations from previous studies are due to the fact that, for example, de Vries,[17] Stoll et al.,[19] and McCook[22] calculate their results based on one hashrate value only (the hashrate measured on the day their analysis was performed) instead of calculating the total amount of hashes actually mined in a year. The study by McCook[22] further uses different assumptions regarding the production of mining equipment and from the documentation available it is not entirely clear how his calculations were done.

The mining of each TH produced 15 $mgCO_2$-eq (coefficient of variation CV = 1.30). For 2018, this makes a total of 17.29 $MtCO_2$-eq This value is lower than what was reported in previous studies: 22 to 22.9 $MtCO_2$-eq,[19] 30.35 $MtCO_2$-eq,[20] and 63 $MtCO_2$-eq.[22] The difference in results is in part due to the fact that the studies already differ with respect to the network's energy consumption. Additionally, the methods of calculating the carbon footprint deviate. Stoll et al. use the average emission factors of power generation in each country and multiply that with the power consumption in that region.[19] Digiconomist assumes that 70% of miners are located in China and the remaining 30% are renewable energies with zero carbon footprint. Thus, Digiconomist takes average emission factor of the Chinese grid and multiplies it by 0.7.[20] Finally, McCook uses the global electricity mix and energy source specific emission factors to calculate the carbon footprint.[22]

Figure 2 displays the carbon footprint of the Bitcoin network in 2018 together with the hashrate and the Bitcoin price in USD. The curves for the hashrate and the carbon footprint are directly proportional as the same impact factor is applied for the entire year (i.e., model parameters are kept constant).

The hashrate reflects the size of the Bitcoin network, of how many miners are trying to gain the right to add the next block. However, the hashrate does not reflect the market price or the

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Table 2. Environmental Impact of 1 TH in the Attributional Baseline Model and All Three Consequential Scenarios According to the IPCC and the ReCiPe Methods

impact category	attributional baseline model	BAU consequential scenario	technology consequential scenario	location consequential scenario
climate change GWP (mgCO_2-eq), IPCC	15.0	13.3	7.74	3.20
climate change GWP (mgCO_2-eq), ReCiPe	14.7	13.1	7.59	3.17
fossil depletion FDP (MJ)	3.74×10^{-06}	3.72×10^{-06}	2.16×10^{-06}	1.15×10^{-06}
metal depletion MDP (kg)	3.36×10^{-07}	6.50×10^{-07}	3.86×10^{-07}	3.65×10^{-07}
human toxicity HTP (kg 1,4-DCB-eq)	5.65×10^{-06}	5.61×10^{-06}	3.34×10^{-06}	3.05×10^{-06}
terrestrial acidification (kg SO_2-eq)	6.04×10^{-08}	3.20×10^{-08}	1.67×10^{-08}	6.87×10^{-11}
freshwater eutrophication (kg P-eq)	6.59×10^{-09}	4.63×10^{-09}	2.73×10^{-09}	2.40×10^{-09}
photochemical oxidation formation POFP (kg ethylene-eq)	4.24×10^{-08}	3.47×10^{-08}	2.00×10^{-08}	5.88×10^{-09}
ozone depletion ODP (kg CFC-11-eq)	4.74×10^{-13}	4.88×10^{-13}	2.83×10^{-13}	3.50×10^{-13}
terrestrial ecotoxicity (kg 1,4-DCB-eq)	7.16×10^{-10}	9.81×10^{-10}	5.74×10^{-10}	4.06×10^{-10}
marine ecotoxicity (kg 1,4-DCB-eq)	3.06×10^{-07}	5.01×10^{-07}	2.92×10^{-07}	3.30×10^{-07}
freshwater ecotoxicity (kg 1,4-DCB-eq)	3.43×10^{-07}	5.72×10^{-07}	3.33×10^{-07}	3.77×10^{-07}

amount of transaction throughput meaning it can—in the short term—increase or decrease independently of both the market price and the transaction throughput.

Table 2 displays the results for computing 1 TH for all the midpoint impact categories considered in this study. McCook[22] also calculates values for eutrophication, acidification, and ecotoxicity based on the global electricity mix. However, the limited documentation provided by McCook[22] on the methodology used does not allow making a comparison with the results of this study.

Hotspot Analysis. A contribution analysis showed that the use phase is the major contributor to carbon footprint with 99.043%. Equipment production and EoL only contribute 0.932% and 0.025%, respectively.

Table 3 shows that four locations alone contribute more than 70% to the total carbon footprint of Bitcoin mining. The table also shows that the share of carbon footprint is larger than the share in mining for a number of locations including Inner Mongolia, Alberta, and Russia. Other locations such as Quebec, Iceland or Sichuan show only a minor individual contribution to the total carbon footprint. This is due to less carbon intensive electricity mixes in these regions. Therefore, installing new mining facilities in those locations, would lead to a decrease in the carbon footprint per TH.

Table 3. Contribution to the Carbon Footprint by Location

location	share in mining	contribution to carbon footprint
Inner Mongolia, China	12.3%	26.2%
Xinjiang, China	10.7%	16.5%
Alberta, Canada	4.7%	16.5%
Russia	4.0%	13.6%
Washington state	6.2%	8.7%
New York state	7.5%	5.4%
Sichuan, China	30.5%	4.6%
Georgia	4.0%	3.2%
British Columbia, Canada	4.1%	2.0%
Iceland	4.0%	1.2%
Sweden	4.0%	1.0%
Norway	4.0%	0.6%
Quebec, Canada	4.0%	0.5%

Looking at the contribution by equipment type, the equipment used in the attributional baseline model contributes to a similar share to mining and to the carbon footprint. For example, the Bitmain Antminer S9 makes up 79.9% of the mining equipment, and contributes 80.7% to the total carbon footprint.

Sensitivity Analysis. The influence of changes in electricity mix on the environmental impact is substantial. Figure 3 shows the results of the sensitivity analysis considering the three different electricity mixes and three different geographical distributions.

The main differences between the three different geographical distributions is largely explained by the different assumptions used in modeling the Chinese miners. The CCAF distribution assumes that 23.2% of miners are located in China,[21] while the attributional baseline model assumes 53.3%, the CoinShares assume 60%,[23] and the Mining Pool model assumes 77.3%. The CoinShares model assumes further that the majority of miners are located in Sichuan, China,[23] where 77% of the electricity is produced from hydropower.[53] It was not possible to estimate shares for locations within Chinese provinces, Canadian provinces, and U.S. states in the Mining Pool model. The fact that the Mining Pool model shows a 71% higher carbon footprint than the attributional baseline model indicates not only the significant impact of mining locations, but also the importance of using accurate information about the geographical location of miners and the electricity mix in such locations. The average electricity mix in China has a different impact than the average mix in Sichuan province, China. On average, 1MJ in China produces 0.313 kg of CO_2-eq, while 1MJ in Sichuan province produces only 0.0974 kg of CO_2-eq according to ecoinvent data.[53,54]

A decrease and increase of 10% of electricity consumption—that could for example, be caused by a change in miner efficiency or cooling requirements—result, respectively, in a decrease and increase of 9.9% of the carbon footprint. The amount of cooling required for Bitcoin mining varies depending on climate, scale of mining facility, and mining equipment used.

A decrease and increase in the hashrate by 10% led to an increase and decrease of 10% of the carbon footprint, respectively. Improving the efficiency of mining equipment is likely to reduce the impact per TH.

A decrease in lifetime of the mining equipment from 1.5 to 1 year led to a minor increase of the carbon footprint by 0.48%,

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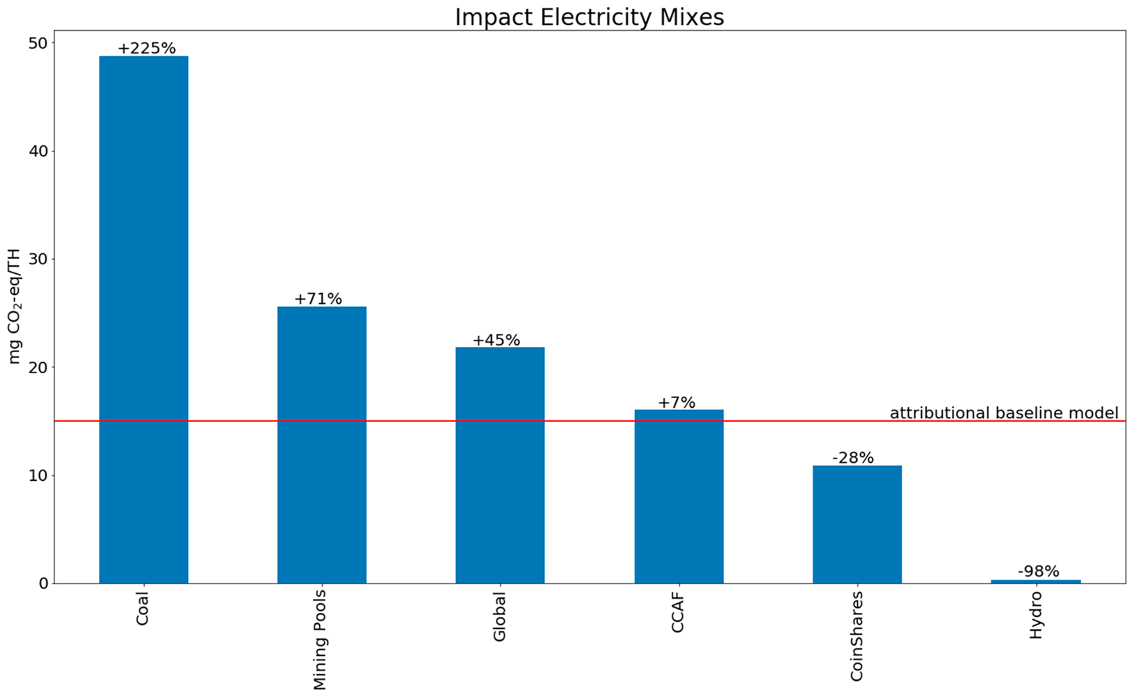

Figure 3. Carbon footprint in $mgCO_2$-eq per TH of the Bitcoin network in 2018 with different electricity mixes and geographical distributions.

whereas an increase to 2 years led to a small decrease of 0.24%. The effect of the lifetime of mining equipment on the carbon footprint is negligible, since the equipment production phase contributes less than 1% to the overall carbon footprint and the use phase—the mining—is highly energy intensive.

Consequential Model and Future Scenarios. While the attributional model answered the question on what was the past impact of the Bitcoin mining network under specific assumptions, the consequential models answer the question of how the carbon footprint would change by increasing the computing demand. Table 2 displays the impact of mining one additional TH for all the midpoint categories considered.

In the BAU scenario, the impact of increasing the demand by one TH results in an impact of 13.3 $mgCO_2$-eq per TH (CV = 0.99). The underlying model assumes that an increase in demand for electricity will be met by the marginal suppliers of electricity in each country.

The carbon footprint of mining one additional TH in the technology scenario assuming more efficient mining equipment was 7.74 $mgCO_2$-eq/TH (CV = 0.54), which is 42% less than in the BAU scenario.

Mining one additional TH in the location scenario leads to a carbon footprint of 3.20 $mgCO_2$-eq/TH (CV = 0.15), which is a 76% improvement to the BAU scenario. Compared to the previous two scenarios the impact categories ozone depletion, marine ecotoxicity and freshwater ecotoxicity increase slightly (see Table 2). This shows that while the carbon footprint in the new locations decreases, renewable energies have higher impacts in other categories.

Additional Relevant Aspects on Bitcoin Mining and Outlook. This study showed that the location of the miners has the highest impact on the environmental impact of the Bitcoin network. Miners will move to locations where electricity prices are very low. Locations with very low electricity prices include those with unused electricity from hydropower (e.g., Sichuan), but also places that use cheap electricity from coal (e.g., Inner Mongolia). The case of Plattsburg (New York) constitutes a recent example of how miners flocking to a city with cheap electricity can increase its energy consumption to the point where the city is no longer able to provide cheap electricity and has to import it from elsewhere.[55] In cases like this, the miners only shift the environmental impact to other users. One way to make sure that Bitcoin mining is truly sustainable would be if the miners established new capacity of renewable energy production ensuring that the marginal electricity consumption is environmentally friendly.

One important challenge in the making of this study was the lack of reliable data sources. Many references listed in this study come from news outlets and grey literature. While Bitcoin has gained a lot of attention in popular media, the academic literature on Bitcoin mining is scarce. Furthermore, the data in peer-reviewed literature is outdated[56,57] considering that in the past couple of months the Bitcoin network has grown substantially (see Figure 2) and any data before late 2017 analyzed a much smaller system than the present one.[12] Therefore, several assumptions such as mining locations and equipment used in this study have been based on gray literature and supported by the Authors' own reflections and assumptions. Due to this scarce and diverging data basis it is important to highlight that this analysis and its results are characterized by an intrinsic uncertainty. Carrying out sensitivity analyses for all parameters was a way to make this uncertainty explicit and to provide an insight on the range of possible outcomes. Further research should focus on a more solid base of data regarding miner location, and mining equipment used. This could be done using both expert interviews and a survey among the miners. Since these two parameters are major influencer of environmental impact, using even more accurate data would substantially decrease model uncertainties.

Another possible way to increase the accuracy of the model is to consider the Bitcoin network as a whole and not focus on Bitcoin mining only. Such research should include impacts

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related to nonmining nodes and the growing number of off-chain transactions. The inclusion of these factors was not coherent with the proposed model and therefore outside the scope of this study. A simple estimation of the lower bound of the energy consumption related to nonmining nodes carried out during this study showed that in 2018 nonmining nodes consumed 0.2 GWh, which is very small compared to the energy consumption of mining. Details on the calculation used to derive this energy consumption is provided in SI Section 6. Uncertainty of this calculation is high, though, as changing the assumptions regarding the computers used by the nodes could lead to a much higher impact, and this uncertainty should be addressed in future research.

This analysis of the Bitcoin mining network contributes with a strictly technical perspective to the broader discussion on the sustainability of the international cryptocurrency. The results should be considered in the larger context of a borderless currency that is difficult to regulate and where political and economic concerns play as important a role as technical and environmental ones. Bitcoin is not only difficult to regulate because it is a global currency, but also because of its governance structure. Any changes of protocol would have to be proposed by developers and then be supported by a sufficient number of miners and users[11] involving a large number of people in the process. Therefore, it is important to remember socio-political aspects, but any discussion concerning regulation should be founded on a technical understanding.

This analysis of the Bitcoin network is not transferable to all applications of blockchain but is limited to the Bitcoin PoW blockchain. The environmental impact of different kinds of blockchains that use a consensus mechanism other than PoW, such as proof-of-stake (PoS), can be expected to be much lower since no electricity-intensive mining is necessary. In order to add a new block in PoS, users who stake a certain amount of cryptocurrency are randomly selected.[1] Thus, no mining is required.

This study further adds a forward-looking perspective. The consequential model helps understanding the environmental impacts associated with future developments of the Bitcoin network. The hashrate of the network is expected to continue growing. For example McCook[22] estimates this growth to be around 5.3% per year. Growing mining efficiency is likely to increase the overall hashrate as a lower electricity consumption per TH means lower electricity costs for the miners. However, in the long term, the hashrate might stagnate as network security reaches a satisfactory level and rates of return for miners might decrease with the shift from Bitcoin rewards to transaction fees as the primary income.[17,57] Modeling these synergistic effects was outside the scope of the current study and should ideally be the subject of future research.

Compared to previous studies on the same topic, this analysis was based on LCA as an established methodology to assess environmental impact and allows an analysis of specific contributors to Bitcoin's environmental impact as well as a prospective assessment. The results of this technical analysis are intended to support stakeholders in the Bitcoin community to assess the severity of Bitcoin's environmental impact, and is expected to contribute in a broader discussion on the future of mining that should inevitably also include social and economic aspects, thus supporting decision-makers in the domain of PoW-based cryptocurrencies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b05687.

Annual energy consumption and carbon footprint by Digiconomist (Section 1); determination of location of miners (Section 2); electricity mixes (Section 3); mining equipment shares and specifications (Section 4); impact assessment (Section 5); and energy consumption of full nodes (Section 6) (PDF)

Online repository[41] with the code for the open source Brightway2 softwar; the model inventories are.csv-files that can be uploaded into the respective python scripts available in the online repository in order to reproduce the results. There is one script for the attributional (retrospective) models and one script for the consequential (prospective) scenarios (ZIP)

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Notes

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